

ATOMIC CARBON IS A TEMPERATURE PROBE IN DARK CLOUDS

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ABSTRACT

We have mapped the C I $^3P_1 \rightarrow ^3P_0$ line at 492 GHz in three molecular clouds immersed in weak ultraviolet radiation fields, TMC-1, L134N, and IC 5146. In all three clouds, the C I peak $T_A^* \sim 1$ K, with very small dispersion. The spatial C I distribution is extended and rather smooth. The $J = 2 \rightarrow 1$ transitions of CO isotopomers were observed at the same angular resolution as C I. The C I peak T_A^* is typically a third of the peak T_A^* of ^{13}CO $J = 2 \rightarrow 1$, and the C I emission is usually more extended than emission in ^{13}CO or C^{18}O $J=2 \rightarrow 1$. The C I linewidth is close to the ^{13}CO $J = 2 \rightarrow 1$ linewidth, larger than the C^{18}O $J = 2 \rightarrow 1$ line width, and smaller than the ^{12}CO $J = 2 \rightarrow 1$ linewidth. The shapes of these lines occasionally differ significantly, probably because of the combined effects of differing opacities and the physical separation of the line forming regions. The uniformity of the C I peak T_A^* is remarkable for a line in the Wien portion of the

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Planck function and indicates a very uniform excitation temperature. This uniformity is best explained if the line is opaque and thermalized. If so, the CI line probes kinetic temperature in clouds exposed to low ultraviolet fluxes. This conclusion has significant implications for the thermal balance in such clouds. At $A_V \simeq 2$, these clouds have a remarkably constant temperature from place to place and from cloud to cloud (7.9 ± 0.8 K). Photodissociation region models of clouds immersed in the mean interstellar radiation field tend to predict stronger lines than we see, but this may be an artifact of assumptions about the temperature.

Subject headings: ISM: abundances — ISM: atoms — ISM: individual (TMC-1, L134N, L183, IC 5146) — ISM: molecules

1. INTRODUCTION

Neutral atomic carbon (C^0) plays an important role in interstellar physics and chemistry. C^0 was recognized long ago as a potentially important coolant for the interstellar medium (Werner 1970; Penston 1970). Furthermore, the abundance of C^0 may reflect the physical structure of molecular clouds (e.g. Stutzki et al. 1988).

Most observations of the submillimeter lines of atomic carbon (C I) have been carried out toward H II regions or reflection nebulae, i.e., toward giant molecular clouds with nearby O and B stars. Such regions, where the ultraviolet (UV) radiation is strong, are good targets to test PDR (“photodissociation region” or “photon-dominated region”) models. Recent PDR models can explain the amount of C^0 relative to CO rather successfully (van Dishoeck & Black 1988; Hollenbach, Takahashi, & Tielens 1991). PDR models for uniform clouds predict that C^0 exists in the surface layer sandwiched between layers where C^+ and CO are the dominant carriers of gas-phase carbon (see Keene et al. 1997 for a review). Observationally, however, the C I distribution is often similar to the CO and ^{13}CO distribution. Most steady-state models predict a very low abundance for neutral carbon in the interior of the cloud ($C^0/\text{CO} < 0.04$ for $A_V > 2.5$ –4, Jansen et al. 1995, Sternberg and Dalgarno 1995), but Le Boulton et al. (1993) have argued that a second solution to the chemical equilibrium equations exists at low densities in which the

neutral carbon abundance is substantially higher ($C^0/CO=0.1-0.3$). Because of strong emission from the PDR, these models cannot be tested in dense, strongly irradiated molecular cores. In principle, one might test them in clouds with low UV fluxes. If substantial C^0 exists in the interiors, it may contribute to the formation of carbon chain molecules, which are abundant in some dark clouds (Suzuki et al. 1992).

Our goals in this work are to determine how C^0 is distributed in clouds exposed to low UV fluxes, and to assess the contribution of such clouds to C I emission from galaxies. Molecular clouds which are not illuminated by strong UV sources have been observed by several researchers (Keene et al. 1987; Stark & van Dishoeck 1994; Ingalls et al. 1994, 1997; Schilke et al. 1995; Stark et al. 1996). In these studies, fewer than ten positions toward each were observed with small (10–15'') beams. The maps of C I emission almost all cover scales of less than 1' toward objects with a size of hundreds of square arc minutes.

In this paper, we present more extensive C I maps and maps of emission from various CO isotopomers toward three clouds immersed in weak UV fields. TMC1 and L134N contain no internal sources of UV radiation. The third source, a molecular cloud associated with IC 5146, contains an HII region, but the portion of the cloud we observed was $1^\circ-1^\circ5$ (20–30 pc) east of the exciting stars. One can parametrize the intensity of UV radiation field incident on the clouds in terms of the average field in the solar neighborhood, I_{UV} (Draine 1978). By comparing the 100 μm intensity observed toward TMC1 and L134N to the intensity predicted from models of opaque clouds exposed to a UV field with a strength comparable to the field in the solar neighborhood (Boulanger & Péroult 1988; Bernard et al. 1990; Hollenbach et al. 1991), we infer that $I_{UV} \sim 1$ for these two clouds. A similar analysis for the region we mapped in IC 5146 leads to the conclusion that $I_{UV} \sim 30$. By studying these sources with weak incident UV fields, we hope to increase our understanding of how UV radiation affects the chemistry and energetics of molecular clouds with low column densities or of the outer portions of more opaque molecular structures.

2. OBSERVATIONS

Observations were carried out with the 10.4 m telescope of the Caltech Submillimeter Observatory (CSO)³ between 1994 January and 1994 April, and in 1994 June, 1995 June, and 1998 March.

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We observed the ground-state fine structure line of neutral carbon ($^3P_1 \rightarrow ^3P_0$, $\nu = 492.1607$ GHz, Frerking et al. 1989) as well as the $J = 2 \rightarrow 1$ transitions of ^{12}CO , ^{13}CO , C^{18}O , and C^{17}O at 219–230 GHz, and the $J = 3 \rightarrow 2$ transitions of ^{12}CO and C^{18}O at 329–346 GHz. For simplicity, we call these two latter frequency bands 230 and 345 GHz. To make C I and CO observations of large areas on the sky in a limited time, we employed a re-imaging device for the Caltech Submillimeter Observatory (CSO), with which the 492 GHz receiver illuminates only one panel of the main dish (Plume & Jaffe 1995; see also Plume et al. 1994, 1999 for studies of molecular clouds with local UV sources with this instrument). With the re-imaging device, the measured telescope beam size (θ_b) and Moon efficiency (η_M) are the same at both 492 and 230 GHz: $\theta_b = 2'.5$ and $\eta_M = 0.8$. At 345 GHz, these parameters have not been measured but are assumed to be the same as those at 492 and 230 GHz. Since the emission is very widespread and smooth, η_M is the appropriate efficiency. Some positions toward L134N were also observed in the on-the-fly (OTF) mapping mode (without the re-imaging device), and then the data were convolved to match the resolution of the re-imaging device. Because the results of the OTF observations are consistent with those of the observations with the re-imaging device, the obtained spectra are co-added to improve the S/N ratio. For selected positions toward TMC-1, observations without the re-imaging device were also carried out on 1994 March 3 and 1994 March 7. For this work, the beam size was $15''$ and the main-beam efficiency was 0.53 at 492 GHz, and the beam size was $32''$ and the main-beam efficiency was 0.76 at 230 GHz.

A technical description of the 230 GHz, 345 GHz, and 492 GHz front-end receivers is given by Kooi et al. (1992), Kooi et al. (1994) and Walker et al. (1992), respectively. The SSB system temperature was 700–5000 K, 700–1100 K, and 180–500 K (SSB) at 492, 345, and 230 GHz, respectively. The receiver backend was a 1024 channel acousto-optic spectrometer. The total bandwidth, channel width, and spectral resolution were 49.7 MHz, 48.5 kHz, and 140 kHz, respectively.

C I spectra were binned to 195 kHz (0.12 km s^{-1}) or 390 kHz (0.24 km s^{-1}) channels depending on the S/N ratio. Data were obtained by position switching against a position shown to have no emission. The spacing interval employed for mapping was $3'$. The line temperature scale was calibrated by using the standard chopper-wheel method. Throughout this paper, we give intensities on the corrected antenna temperature (T_A^*) scale (see Kutner & Ulich 1981 for definition). The calibration assumes that the signal and image sidebands have equal gain.

We observed the classical “dark” clouds, TMC-1 and L134N (a.k.a L183) and a portion of the cloud associated with IC 5146. In addition, we use data toward regions with local UV sources, Orion A (this work), Cep A, NGC 2024, S140, and W3 (Plume et al. 1999), for comparison. The reference center, off position, and observed lines for each object are listed in Table 1.

3. RESULTS

For all the observations, we removed a first order baseline, determined an integrated intensity from the area under the line, and fit a Gaussian to determine peak T_A^* . While some lines were non-Gaussian, the fits always provided a good estimate of the peak T_A^* .

3.1. TMC-1

The distance to TMC-1 is 140 pc (Elias 1978; Cernicharo et al. 1985). At this distance, the beamsize of the re-imager ($2'.5$) corresponds to 0.10 pc. Figures 1(a) and (b) show the distribution of the C I and $^{13}\text{CO } J = 2 \rightarrow 1$ spectra on the sky. The map center (Table 1) is the cyanopolyne peak (Churchwell, Winnewisser, & Walmsley 1978), and the map size is $18'$ (EW) \times $33'$ (NS) (or $0.7 \text{ pc} \times 1.3 \text{ pc}$). The peak line temperature decreases slowly away from the map center, except to the south. The mean $\int T_A^*(\text{C I}) dV$ is $1.7 \pm 0.3 \text{ K km s}^{-1}$. (Throughout the paper, the uncertainty reflects the standard deviation of the distribution, not the error in the mean.) The corresponding values for T_A^* are $1.1 \pm 0.3 \text{ K}$ (Fig. 12). The “TMC-1 ridge”, which is a $\sim 2'$ -wide NW-SE ridge passing through the map center in high-density tracers such as NH_3 , CCS and HC_3N (Little et al. 1979; Hirahara

et al. 1992), is not prominent in C I or ^{13}CO . Figure 2 shows the distribution of the $\int T_A^* dV$ along (a) $\Delta\alpha = 0''$ and (b) $\Delta\delta = 0''$. The distribution of $\int T_A^*(\text{C I}) dV$, like that of $^{13}\text{CO } J = 2 \rightarrow 1$, is fairly flat across the source, while the $\text{C}^{18}\text{O } J = 2 \rightarrow 1$ and $\text{C}^{18}\text{O } J = 1 \rightarrow 0$ (Langer et al. 1995) peak more sharply at the map center.

The C I and $^{13}\text{CO } \int T_A^* dV$ correlate very poorly in this source. From all the points in the re-imager map of TMC-1, we obtained a least-squares fit to a relation between the $\int T_A^* dV$ of:

$$\int T_A^*(\text{C I}) dV = (1.1 \pm 0.4) + (0.19 \pm 0.11) \int T_A^*(^{13}\text{CO}) dV$$

where the correlation coefficient was 0.32.

This poor correlation contrasts with the strong correlations (correlation coefficient 0.85) found in large-scale observations of UV-illuminated molecular clouds (Plume et al. 1999) and the even stronger correlations in the cloud cores themselves (Keene et al. 1997). In our large-scale TMC1 map, the C I profile does not always resemble the ^{13}CO profile. To see the difference in the line shape more clearly, we averaged the spectra of three positions: $(\Delta\alpha, \Delta\delta) = (0'', -1260'')$, $(0'', -1080'')$, and $(0'', -900'')$. Figure 3 shows the average spectra of $\text{CO } J = 2 \rightarrow 1$, $^{13}\text{CO } J = 2 \rightarrow 1$, $\text{C}^{18}\text{O } J = 2 \rightarrow 1$, and C I. The C I profile is flat-topped with almost constant temperature from 5.3 to 7 km s^{-1} . The $^{13}\text{CO } J = 2 \rightarrow 1$ profile has a sharp peak at 5.5 km s^{-1} , a broad plateau, and then a second peak at $\sim 6.8 \text{ km s}^{-1}$.

If some of the C I emission arises in high column density molecular cores and if the C° abundance depends on the local chemistry, changes in that chemistry might affect the strength of the C I emission. To investigate this possibility, we measured the $\int T_A^* dV$ of C I and ^{13}CO at the cyanopolyne peak $(0'', 0'')$ and at the ammonia peak $(\Delta\alpha, \Delta\delta) = (-290'', 380'')$ (e.g., Hirahara et al. 1992; Pratap et al. 1997). Because the ammonia peak position does not match our observation grid, we average the spectra at $(-360'', 360'')$ and at $(-180'', 360'')$. $\int T_A^*(\text{C I}) dV$ is 2.0 and 1.8 K km s^{-1} at the cyanopolyne and ammonia peaks, respectively, while the $^{13}\text{CO } \int T_A^* dV$ is 4.6 and 4.9 K km s^{-1} . There is *no* significant peak of the C I line at the cyanopolyne peak; if deep C° contributes to long chain carbon molecules, it is not visible in this line.

To see the C I line temperature and spectral variation on smaller scales, we observed the detailed line emission distribution across the TMC-1 ridge with the fully illuminated CSO (beamsize $15''$ for C I, $30''$ for $\text{C}^{18}\text{O } 2 \rightarrow 1$). Figure 4 shows

C I and C¹⁸O $J = 2 \rightarrow 1$ spectra. The grid spacing was $\sqrt{2} \times 20''$ from NE to SW. The C I and C¹⁸O $\int T_A^* dV$ distribution is rather featureless on this (1') scale. The mean value of $\int T_A^*(C\ I)dV$ is 2.18 K km s⁻¹ with a standard deviation of ± 0.36 K km s⁻¹. For C¹⁸O $J=2 \rightarrow 1$, we find $\int T_A^* dV = 1.31 \pm 0.19$ K km s⁻¹. The C I profile is broader than that of C¹⁸O $\langle \Delta V(C\ I)/\Delta V(C^{18}O) \rangle = 1.9 \pm 0.5$. Our results are consistent with those of Schilke et al. (1995), who observed the region with the same telescope but with a somewhat different reference center.

3.2. L134N

The distance to L134N is 110 ± 10 pc (Franco 1989). The cloud is isolated, and it shows no star forming activity in far-infrared observations (Sargent et al. 1983; IRAS Point Source Catalog 1985). L134N has been extensively observed in various molecular lines (Swade 1989). Phillips & Huggins (1981) previously detected C I at one position and Keene (1995) has made a 20' long strip-map of C I in this source. Figure 5 shows spectra obtained in an area of 12' (EW) \times 30' (NS) (0.4 pc \times 1.0 pc). The beamsize using the re-imager corresponds to 0.08 pc. For C I, the $\int T_A^* dV$ distribution is remarkably uniform; the mean and standard deviation are 1.5 ± 0.5 K km s⁻¹. The mean T_A^* is 1.1 ± 0.2 K (Fig. 12).

Figures 6(a) and (b) compare the C I and CO isotopomer spectra at the map center. The C I profile peaks at 6.8 km s⁻¹ and has a prominent blue wing extending to $V_{LSR} = 0$ km s⁻¹. The ¹³CO, C¹⁸O, and C¹⁷O $J = 2 \rightarrow 1$ and ¹²CO and C¹⁸O $J=3 \rightarrow 2$ lines differ significantly in their widths, shapes, and central velocities. These differences imply that line opacity and/or isotopic fractionation effects influence the shapes of most of these lines.

Figure 7 shows the $\int T_A^* dV$ distribution along $\Delta\alpha = 180''$. The C I distribution is very flat, varying by only 20% along a strip more than half a degree (1 pc) long. As in TMC1, the correlation between the C I and ¹³CO $\int T_A^* dV$, based on the entire map, is poor:

$$\int T_A^*(C\ I)dV = (0.94 \pm 0.29) + (0.14 \pm 0.07) \int T_A^*(^{13}\text{CO}) dV$$

where the correlation coefficient was 0.41.

Stark et al. (1996) observed six positions along a 10'-long East-West strip in

L134N with the James Clerk Maxwell Telescope. They found that the distribution of $\int T_A^*(C\ I)dV$ is similar to those of $^{13}\text{CO } J = 3 \rightarrow 2$ and $J = 2 \rightarrow 1$ but not to $\text{C}^{18}\text{O } J = 2 \rightarrow 1$. Our result shows that the distribution of $\int T_A^*(C\ I)dV$ is flatter than those of ^{13}CO and $\text{C}^{18}\text{O } J = 2 \rightarrow 1$. Ratios of $^{13}\text{CO}/\text{C I } \int T_A^*dV$ vary from 1.8 to 3.0 along this strip. The distribution of $\int T_A^*(C\ I)dV$ is also substantially more extended than the emission in the many molecular transitions observed by Swade (1989), including $\text{C}^{18}\text{O } J = 1 \rightarrow 0$, $\text{CS } J = 2 \rightarrow 1$, $\text{NH}_3\ J, K = 1, 1$, $\text{H}^{13}\text{CO}^+ J = 1 \rightarrow 0$, and $\text{C}_3\text{H}_2\ J_{K-K^+} = 1_{10} \rightarrow 1_{01}$.

3.3. Cases with Local Ultraviolet Sources

3.3.1. IC 5146

IC 5146 (distance = 1.0 kpc, Walker 1959) is an open cluster with an H II region. At 1 kpc distance, the beamsize of the re-imager corresponds to 0.7 pc. A neutral cloud associated with the H II regions has been observed in molecular lines by Dobashi et al. (1992), Lada et al. (1994), and Kramer et al. (1999). Figure 8 shows spectra observed in an area of $39'$ (EW) \times $21'$ (NS) ($11.8\text{ pc} \times 6.4\text{ pc}$). The reference center is the position of IC 5146. We have observed a region $\sim 60' - 90'$ away from the H II region. Observations of this portion of IC 5146 serve as a bridge between the study of clouds immersed in the weak ambient UV field in the outer Galaxy and regions illuminated by prominent local UV sources. $\int T_A^*(C\ I)dV$ is $2.0 \pm 0.9\text{ K km s}^{-1}$ over the mapped region. The peak T_A^* is typically about 1 K (0.9 ± 0.3 , Fig. 12). Despite our estimates of somewhat higher I_{UV} in this region, the lines are not significantly stronger.

Figure 9 shows the $\int T_A^*dV$ distribution along $\Delta\delta = 1380''$. The C I and ^{13}CO intensities are poorly correlated. From all the IC 5146 data, we obtain

$$\int T_A^*(C\ I)dV = (1.18 \pm 0.53) + (0.22 \pm 0.12) \int T_A^*(^{13}\text{CO}) dV$$

with a correlation coefficient of 0.44.

3.3.2. Other Sources

In order to understand the differences between C I emission from sources with different I_{UV} , we make use of large-scale C I and CO isotopomer maps of high- I_{UV} sources. The data include points from the maps of Cep A, NGC 2024, S140, and W3 made with the re-imager by Plume et al. (1999). In addition, as part of the present work, we have mapped a $15' \times 25'$ region in Orion A with the re-imaging device. Figure 10 shows the $\int T_A^* dV$ maps of Orion A in the C I $^3P_1 \rightarrow ^3P_0$ and $^{13}\text{CO } J = 2 \rightarrow 1$ emission. I_{UV} for regions 2–15 arcmin from θ^1 C Orion ranges from 10 to 10^5 (Stacey et al. 1993). The T_A^* is much higher and more variable than that in the clouds with low UV fluxes: mean T_A^* is 3.8 ± 1.1 . White & Sandell (1995) observed a smaller part of the Orion A cloud in C I with the James Clerk Maxwell Telescope. With its smaller beam, they found that the distribution of C I is often different from that of ^{13}CO . Nonetheless, Keene et al. (1997) show that C I emission correlates well with ^{13}CO emission in Orion at moderate intensity levels. In our data, the C I emission on the map is doubly peaked around $(\Delta\alpha, \Delta\delta) = (0'', -300'')$ and $(0'', 0'')$, while the ^{13}CO emission does not show double peaks. Our map is consistent with the map of White & Sandell (1995), if the difference in beamsize is taken into account.

Figure 11 plots the C I $\int T_A^* dV$ versus the $^{13}\text{CO } \int T_A^* dV$ for the three dark clouds (low- I_{UV}) as well as for the five high- I_{UV} molecular clouds. A least-squares fit to the data from all of the high- I_{UV} sources gives:

$$\int T_A^*(\text{C I}) dV = (3.8 \pm 0.3) + (0.25 \pm 0.02) \int T_A^*(^{13}\text{CO}) dV$$

with a correlation coefficient of 0.75, clearly a stronger correlation than found for the low- I_{UV} clouds. The dark cloud points cluster among the points from the high- I_{UV} clouds with the lowest C I and $^{13}\text{CO } J = 2 \rightarrow 1 \int T_A^* dV$. The overlapping points from the high- I_{UV} clouds mostly represent regions near the edges of the clouds and often those parts of the clouds with the smallest amounts of incident UV radiation (Plume et al. 1999). Even in aggregate, the dark clouds show little or no correlation of C I and $^{13}\text{CO } \int T_A^* dV$.

3.4. Intensity and Linewidth

Since the mean T_A^* is similar in all the low-uv clouds, including IC5146, we combined them to find the distribution in Fig. 12; the mean T_A^* is 1.0 ± 0.3 . This is a far lower value and a tighter distribution than is seen in clouds exposed to higher UV fluxes.

In contrast, the linewidths, relative to CO isotopes, are similar to those in high- I_{UV} clouds. Plume et al. (1999) obtained $\langle \Delta V(\text{C I}) / \Delta V(^{13}\text{CO}) \rangle = 1.08 \pm 0.3$ and $\langle \Delta V(\text{C}^{18}\text{O}) / \Delta V(^{13}\text{CO}) \rangle = 0.78 \pm 0.2$ for massive star forming regions with local UV. For TMC1, L134N, and IC 5146, we measured the linewidth ratio in the same way to be $\langle \Delta V(\text{C I}) / \Delta V(^{13}\text{CO}) \rangle = 0.97 \pm 0.21$ and $\langle \Delta V(\text{C}^{18}\text{O}) / \Delta V(^{13}\text{CO}) \rangle = 0.58 \pm 0.16$, which are similar to the results for sources with stronger local UV. Here, we used spectra toward $(\Delta\alpha, \Delta\delta) = (0'', -720'') - (0'', 180'')$ in TMC-1, $(0'', 0'')$ and $(180'', -540'') - (180'', 360'')$ in L134N, and $(-5580'', 1380'') - (-5220'', 1380'')$ and $(-4320'', 1380'') - (-3960'', 1380'')$ in IC 5146 where both lines were observed and the line shape is not so much different from a Gaussian profile. The absolute values of the linewidth are $\Delta V(\text{C I}) = 1.3 \pm 0.4 \text{ km s}^{-1}$, $\Delta V(\text{C}^{18}\text{O}) = 0.7 \pm 0.2 \text{ km s}^{-1}$, and $\Delta V(^{13}\text{CO}) = 1.3 \pm 0.2 \text{ km s}^{-1}$ for TMC-1 and L134N. Those for IC 5146 are $\Delta V(\text{C I}) = 1.5 \pm 0.4 \text{ km s}^{-1}$, $\Delta V(\text{C}^{18}\text{O}) = 1.3 \pm 0.5 \text{ km s}^{-1}$, and $\Delta V(^{13}\text{CO}) = 1.8 \pm 0.4 \text{ km s}^{-1}$. When we compare the C I linewidth with the ^{12}CO linewidth, we obtain $\langle \Delta V(\text{C I}) / \Delta V(^{12}\text{CO } 2 \rightarrow 1) \rangle = 0.62 \pm 0.05$ for $(\Delta\alpha, \Delta\delta) = (0'', -720'') - (0'', 180'')$ in TMC-1.

4. DISCUSSION

We have detected widespread, remarkably uniform C I emission from TMC1 and L134N, and from a portion of the IC 5146 cloud far from the OB star cluster. The C I emission is more extended than the emission in the $J = 2 \rightarrow 1$ transitions of ^{13}CO and C^{18}O and the strength of the C I line correlates poorly with the $\int T_A^* dV$ for these two CO isotopomers. In this section, we examine the implications of these observations of clouds with low- I_{UV} for the origin of the C I emission, for cloud chemistry, and for the thermal structure of dark clouds.

4.1. Photodissociation Regions Explain the Observed C I Emission

In our previous paper (Plume et al. 1999), we studied the C I $^3P_1 \rightarrow ^3P_0$ emission from giant molecular clouds bathed in radiation fields 10-1000 times stronger than the mean interstellar field in the solar neighborhood. We showed that this emission arises from a neutral atomic carbon layer in a photodissociation region at the cloud surface. The measured column densities and intensities agree well with the values predicted by the theoretical models. Both the independence of C I $\int T_A^* dV$ from the strength of the UV field and the higher C I/ ^{13}CO ratios at the cloud edges also support the conclusion that the C I emission comes from the photodissociated material at the atomic/molecular interface. We would now like to use the C I and CO isotopomer maps of TMC1 and L134N, clouds with $I_{UV} \sim 1$, to examine the case for PDR's as the source for the C I emission from clouds immersed in lower UV fields than those incident on the GMC's.

Figure 11 plots the C I $\int T_A^* dV$ versus the strength of the ^{13}CO $J=2 \rightarrow 1$ line for the positions we have observed in TMC1 and L134N and, for comparison, the positions in IC 5146 and other clouds illuminated by stronger local UV fields. The figure shows that the C I $\int T_A^* dV$ in TMC1 and L134N are comparable to those observed in IC 5146, and comparable to those at the weakest points observed in the extended molecular clouds near OB stars observed by Plume et al. (1999). In this figure, we also present theoretical C I and ^{13}CO $\int T_A^* dV$ calculated on the basis of column densities predicted by models of translucent clouds illuminated by UV radiation (van Dishoeck and Black 1988). The models include the effects of isotope-selective photodissociation and isotopic fractionation and assume a carbon depletion factor, δ_C of 0.4. The open squares represent models T3 to T6, clouds illuminated by $I_{UV} = 1$ and total cloud extinction, A_V^{tot} , from 2.0 to 5.1. The open circles represent models I4 to I7, clouds illuminated by $I_{UV}=10$ and total cloud extinction, A_V^{tot} , from 2.7 to 9.0. We calculated the $\int T_A^* dV$ from the model C^0 and ^{13}CO column densities using a Large Velocity Gradient (LVG) (Scoville & Solomon 1974; Goldreich & Kwan 1974) non-LTE excitation and radiative transfer code to account, in a crude way, for excitation and opacity effects. We used the rate coefficients for collisional excitation of C I from Schröder et al. (1991). The C^0 and ^{13}CO column densities in the models do not depend strongly on the kinetic temperature assumed by van Dishoeck and Black (see their models T6A and T6B). Uncertainties in predicted intensities from our LVG calculations therefore

depend directly on the assumed kinetic temperature rather than indirectly through linewidth-dependent photochemical effects. In this rough comparison, we have used $T_K=10$ K to be consistent with measures of core temperatures in dark clouds (e.g. Benson & Myers 1980). We set the column density per unit velocity in the radiative transfer model equal to the C^o or ¹³CO column density from the theoretical model divided by the typical linewidth in the clouds. The results in Figure 11, where we have multiplied the model $\int T_A^* dV$ by the beam efficiency to compare to the observations, show that the van Dishoeck and Black models for $I_{UV}=1$ correctly predict the C I $\int T_A^* dV$ we observe in the maps of TMC1 and L134N. The observed ¹³CO $\int T_A^* dV$ are comparable to the values for the models with the largest A_V^{tot} .

The morphology of the C I and molecular emission from the clouds with $I_{UV} \sim 1$ also supports the idea that the C I line arises in material at the cloud surface. In both L134N and TMC1, the C I $\int T_A^* dV$ distribution is broader and flatter than that of ¹³CO and significantly broader than the C¹⁸O J=2→1 distribution.

4.2. Why Don't C I and Molecular Line Intensities Correlate in Low- I_{UV} Clouds?

If the C I emission arises in a thin layer near the cloud surface and emission from molecular lines less opaque than the lowest few transitions of ¹²CO arise throughout the bulk of the cloud, there is no *a priori* reason to expect the C I and ¹³CO or C¹⁸O $\int T_A^* dV$ to correlate. Nevertheless, the C I and CO isotopomer $\int T_A^* dV$ correlate astonishingly well in high column density cloud cores illuminated by powerful UV fields like M17 SW (Keene et al. 1997). There is a clear difference in the $\int T_A^* dV$ correlation between high- I_{UV} clouds (correlation coefficient = 0.85 for C I vs. ¹³CO $\int T_A^* dV$ Plume et al. 1999) and the low- I_{UV} dark clouds studied here (correlation coefficient = 0.32 and 0.41 for C I vs. ¹³CO in TMC1 and L134N, respectively).

For cloud cores, Plume et al. (1999) point out the similarity of the clump/interclump structure needed to produce the observed extent of the C II 158 μ m line emission to the kind of structure that would produce the high degree of spatial correlation between C I and ¹³CO seen by Keene et al. (1997); in both cases the $\int T_A^* dV$ reflect the number of clumps in the beam. Plume et al. argue that in extended GMC material, unlike the high column density cores, the C I lines arise

predominantly in a global layer over the entire face of the cloud. They explain the somewhat weaker C I– ^{13}CO $\int T_A^* dV$ correlation as a conspiracy of edge effects and the correlation of temperature and density variations with total column density. The lack of intensity correlations in TMC1 and L134N, then, results from an absence of temperature variations as well as from higher opacities in C I $^3\text{P}_1 \rightarrow ^3\text{P}_0$ and the lowest transitions of ^{13}CO and C^{18}O at low temperature (see below). As is so dramatically illustrated in the small-scale C I–molecular line comparisons toward the TMC1 ridge (Figure 4 and Schilke et al.), the C I observations toward clouds illuminated by $I_{UV} \sim 1$ external fields do not contain any information about high column density molecular regions.

4.3. Thermal Balance: The Meaning of Constant C I Line Brightness

The most striking feature of the data are the very narrow distributions of T_A^* seen in Fig. 12. Such tight distributions are not seen in any molecular line besides CO, which is opaque and thermalized. We suggest that the CI lines are also opaque and thermalized; thus the values of T_A^* provide a probe of T_K in the PDR layer with $\tau \sim 1$.

There are both observational and theoretical arguments for a high opacity in the C I $^3\text{P}_1 \rightarrow ^3\text{P}_0$ line. The large linewidth and, in TMC1, flat-topped shape of the C I lines are both indications that the opacity is high. Furthermore, the peak intensity does not vary strongly despite significant variations in line width (Figures 1a, 5, and 8). If the lines were not thermalized, T_A^* would be very sensitive to density fluctuations and the tight distribution seen in Fig. 12 would be extremely unlikely. To investigate the C I opacity more thoroughly, we also computed spherical Monte Carlo models (Choi et al. 1995) for photodissociated clouds. The temperature and C I abundance versus distance output from a plane parallel PDR model with $I_{UV}=1$ and $n_{\text{H}+2\text{H}_2}=10^3 \text{ cm}^{-3}$ was mapped onto a spherical cloud (see Pak et al. 1998, van Dishoeck & Black 1987) with a microturbulent velocity dispersion of 0.65 km s^{-1} . The model, which has a line center opacity ~ 2 , correctly reproduces the linewidths seen in the $^3\text{P}_1 \rightarrow ^3\text{P}_0$ spectra. Assumptions about the cloud core temperature (see below) may mean that the C I opacity is even higher. Because the critical density for the $^3\text{P}_1 \rightarrow ^3\text{P}_0$ transition is only 800 cm^{-3} and the photon escape probabilities are substantially lower than unity, it is very likely that

the transition is thermalized ($T_{ex} = T_K$).

If the C I line is opaque and thermalized, it provides a probe of T_K deep in the PDR layer, where $\tau \sim 1$. The distribution of T_K is shown in Fig. 13 for all the dark clouds and for Orion A. The distribution for the dark clouds is remarkably tight: mean T_K is 7.9 ± 0.8 K, a 10% variation. The high frequency of the C I $^3P_1 \rightarrow ^3P_0$ transition means that it is in the Wien limit for the temperatures we derive; thus a tight distribution in T_A^* (30% variation) becomes even tighter in T_K . Small variations in temperature would lead to an enormous fractional change in observed T_A^* ($T_K=8\pm3$ K implies, for thermalized gas, a T_A^* range from 0.17 to 2.5 K, a factor of 15). In comparison, the range of T_K inferred for Orion is much broader, consistent with a lower and more variable opacity; thus the values of T_K in Orion are lower limits.

Do these values of T_K agree with predictions of PDR models for low- I_{UV} ? The PDR models discussed above produce $T_K \sim 11.5$ K in the line forming region. This higher T_K results in a ~ 3 K C I line. The high predicted temperature may be, in part, an artifact of the assumption that the asymptotic cloud core temperature was 10 K or of slight differences between the actual and theoretical thermal balance. Recent models by Kaufman et al. (1999) find that T_K drops below 10 K for very small ratios of I_{UV} to density. Comparison to their predictions of intensity finds agreement with our observations only at low I_{UV} and quite high density ($n > 10^5$ cm $^{-3}$). Is there other evidence for such low T_K in low- I_{UV} clouds? Clemens, Yun, & Heyer (1991) found that 74% of a sample of such clouds have $T_K = 8.5$ K.

Why do the C I layers have such a constant temperature? Given the inevitability of density fluctuations, what causes the thermal balance to choose this temperature? One strong possibility is that neutral carbon itself provides the thermostat. The fact that the C I line is in the Wien portion of the Planck function at these low T_K means that the cooling power in the 492 GHz line rises very rapidly with temperature in the 5-10 K range. In the specific layer where C I is present, the higher opacity of the ^{12}CO line and the low abundance of ^{13}CO may keep the rotational lines of CO isotopomers from contributing strongly to the cooling. Indeed models by Hollenbach, Takahashi, & Tielens (1991) indicate that C I cooling does dominate in the layer where neutral atomic carbon is abundant.

If our interpretation is correct, the higher transition of C I, $^3P_2 \rightarrow ^3P_1$ at 809 GHz, will be very weak toward these clouds. An upper limit can be obtained by

assuming that the higher transition is also opaque and thermalized. In this case, the radiation temperature (or T_A^*/η_M) is 0.3 K. However, the higher line is very unlikely to be opaque. Even if the levels are thermalized, the optical depth in the higher line will be only 0.16 that of the lower line. More realistic estimates can be obtained from models of clouds in weak UV fields, combined with LVG calculations. Model T6 ($n = 10^3 \text{ cm}^{-3}$, $A_V^{tot} = 5.1 \text{ mag}$) of van Dishoeck & Black (1988) and LVG calculation with $T_K = 8 \text{ K}$ predict the $^3P_1 \rightarrow ^3P_0$ and $^3P_2 \rightarrow ^3P_1$ radiation temperatures to be 0.9 K and 0.02 K, respectively. Model T6C with higher density ($n = 10^4 \text{ cm}^{-3}$) and LVG calculation with $T_K = 8 \text{ K}$ predict the $^3P_1 \rightarrow ^3P_0$ and $^3P_2 \rightarrow ^3P_1$ radiation temperatures to be 1.1 and 0.04 K, respectively. The expected ratio of $^3P_2 \rightarrow ^3P_1$ to $^3P_1 \rightarrow ^3P_0$ is thus less than 0.05. To the authors' knowledge, no observations of C I $^3P_2 \rightarrow ^3P_1$ toward molecular clouds in weak UV fields have been reported in the literature.

4.4. Overall Cooling by C I

The C I $^3P_1 \rightarrow ^3P_0$ line was expected to play an important role in interstellar gas cooling (Penston 1970). The relevant quantity here is $F = \int \int I_\nu d\nu d\Omega$; because $F \propto \nu^3 \int T_A^* dV$, C I may be more important than one might guess from the ratios of $\int T_A^* dV$. We derive $F(\text{C I})/F(^{12}\text{CO } J=2 \rightarrow 1) = 1.9 \pm 0.3$ for TMC-1 and 1.0 ± 0.5 for IC 5146. The ratio $F(\text{C I})/F(^{12}\text{CO } J=3 \rightarrow 2)$ in L134N is 0.8 ± 0.2 . In these dark clouds, the cooling power of the C I $^3P_1 \rightarrow ^3P_0$ line is as important as low- J ^{12}CO lines. The flux ratios in the average spectrum of the Galaxy (Wright et al. 1991) are $F(\text{C I})/F(^{12}\text{CO } J=2 \rightarrow 1) = 2.3$ and $F(\text{C I})/F(^{12}\text{CO } J=3 \rightarrow 2) = 1.6$.

5. Summary

We have mapped the C I $^3P_1 \rightarrow ^3P_0$ transition in three clouds with low- I_{UV} values at their surfaces. The C I emission is more extended than emission in low- J CO isotopomer lines and the intensity is very uniform. C I linewidths are significantly larger than C^{18}O linewidths and comparable to or larger than the widths of low- J ^{13}CO lines. The uniform intensity and large linewidth of the C I lines, as well as models of low- I_{UV} photodissociation regions imply that the C I

$^3\text{P}_1 \rightarrow ^3\text{P}_0$ transition is thermalized and optically thick. The uniform $T_A^*=1.0\pm0.3$ K, together with the high frequency of the C I line, means that the kinetic temperature in the emitting layer is remarkably constant, $T_K(\text{C I layer})=7.9\pm0.8$ K. We suggest that the C I emission itself acts as a thermostat in controlling the temperature of this layer in low- I_{UV} clouds.

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Table 1: REFERENCE CENTER AND OFF POSITION

Source	Reference $\alpha(1950)$	Center $\delta(1950)$	Off $\Delta\alpha$	Position $\Delta\delta$	Observed Line
TMC-1	$4^h 38^m 38^s.6$	$25^\circ 36' 00''$	$2400''$	$0''$	C I, $J = 2 \rightarrow 1$ of ^{12}CO , ^{13}CO , C^{18}O
Orion A	$5^h 32^m 47^s$	$-5^\circ 24' 23''$	$1800''$	$1800''$	C I, $J = 2 \rightarrow 1$ of ^{13}CO , C^{18}O
L134N	$15^h 51^m 30^s$	$-2^\circ 43' 31''$	$-660''$	$660''$	C I, $J = 2 \rightarrow 1$ of ^{13}CO , C^{18}O , C^{17}O , $J = 3 \rightarrow 2$ of C^{18}O
"	"	"	$-1800''$	$0''$ ^a	$J = 3 \rightarrow 2$ of ^{12}CO
IC 5146	$21^h 51^m 54^s$	$47^\circ 01' 12''$	$-3000''$	$0''$	C I, $J = 2 \rightarrow 1$ of ^{12}CO , ^{13}CO , C^{18}O

^a Off position is in (ΔAZ , ΔEL) for this line only

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Fig. 1.— Line profiles toward TMC-1. The (0,0) position was $\alpha(1950) = 4^h 38^m 38^s.6$, $\delta(1950) = 25^\circ 36' 00''$. These data were taken with the re-imager with a $150''$ beam. The intensity scale is T_A^* . (a) C I $^3P_1 \rightarrow ^3P_0$, rebinned to 0.24 km s^{-1} channel spacing. (b) $^{13}\text{CO } J = 2 \rightarrow 1$.

Fig. 2.— Distribution of $\int T_A^* dV$ toward TMC-1, along (a) $\Delta\alpha = 0''$ (b) $\Delta\delta = 0''$. Open circles, open boxes, and filled circles represent the $\int T_A^* dV$ of $^{13}\text{CO } J = 2 \rightarrow 1$, $\text{C}^{18}\text{O } J = 2 \rightarrow 1$, and C I $^3P_1 \rightarrow ^3P_0$, respectively. The error bars reflect only the rms noise level.

Fig. 3.— Line profiles observed with the re-imaging device toward TMC-1. C I spectra were binned to 0.24 km s^{-1} channels, and some of the CO isotopomer spectra were binned to 0.12 km s^{-1} channels. The spectra are sums of data taken at three positions: $(\Delta\alpha, \Delta\delta) = (0'', -1260'')$, $(0'', -1080'')$, and $(0'', -900'')$.

Fig. 4.— C I $^3P_1 \rightarrow ^3P_0$ (left) and $\text{C}^{18}\text{O } J = 2 \rightarrow 1$ (right) spectra obtained toward TMC-1 with the full CSO telescope (beamsize $15''$ for C I and $32''$ for $\text{C}^{18}\text{O } J = 2 \rightarrow 1$).

Fig. 5.— C I line profiles toward L134N. These data were taken with the re-imaging device with a $150''$ beam. The intensity scale is T_A^* . The (0,0) position was $\alpha(1950) = 15^h 51^m 30^s$, $\delta(1950) = -2^\circ 43' 31''$. Spectra were binned to 0.24 km s^{-1} .

Fig. 6.— A comparison of line profiles observed with the re-imaging device at the map center for L134N. (a) The $J = 2 \rightarrow 1$ transitions of ^{13}CO , C^{18} , and C^{17}O , and C I. C I, C^{18}O , and C^{17}O spectra were binned to 0.24 km s^{-1} channels. (b) The $J = 3 \rightarrow 2$ transitions of ^{12}CO and C^{18}O . The spectra were binned to 0.24 km s^{-1} channels.

Fig. 7.— Distribution of $\int T_A^* dV$ along $\Delta\alpha = 180''$ in L134N. The symbols are the same as those used in Figure 2.

Fig. 8.— C I line profiles toward IC 5146. The (0,0) position for this map was $\alpha(1950) = 21^h 51^m 54^s$, $\delta(1950) = 47^\circ 01' 12''$.

Fig. 9.— Distribution of the $\int T_A^* dV$ along $\Delta\delta = 1380''$ in IC 5146. The symbols are the same as those used in Figure 2.

Fig. 10.— Map of $\int T_A^* dV$ of C I $^3P_1 \rightarrow ^3P_0$ (solid lines) and $^{13}\text{CO } J=2 \rightarrow 1$ (dotted lines) toward Orion A. The contour interval is 3 K km s $^{-1}$ for C I and 10 K km s $^{-1}$ for ^{13}CO .

Fig. 11.— A plot of C I $\int T_A^* dV$ against that of $^{13}\text{CO } J=2 \rightarrow 1$. The filled diamonds, triangles, and boxes represent values observed toward TMC-1, L134N, IC 5146, respectively. The dots represent points from the GMC's observed for this paper and by Plume et al. (1999). The connected open symbols represent C I and $^{13}\text{CO } \int T_A^* dV$ predicted by an LVG model and column densities from the PDR chemistry models of van Dishoeck & Black (1988). The open squares represent models T3-T6, for $I_{UV}=1$ and total cloud extinction, A_V^{tot} , from 2.0 to 5.1. The open circles represent models I4-I7, for $I_{UV}=10$ and total cloud extinction, A_V^{tot} , from 2.7 to 9.0.

Fig. 12.— The lower three panels show the distribution of T_A^* for the three low- I_{UV} clouds, with the mean and standard deviation indicated. The distribution for all three dark clouds is shown in the upper left, while that for Orion (note very different scale) is shown in the upper right.

Fig. 13.— The distribution of T_K , assuming that the lines are opaque and thermalized, is shown for all the dark clouds and for Orion A. The assumption that the line is opaque is probably not valid in Orion A, so these represent lower limits to T_K .































